action can hardly diminish more rapidly than according to the inverse third power. If Jupiter has an effect, mass or size must come into play. I have added the last column to show the relative position of the planets with regard to their size and distance, irrespective of mass.

The Production of Characteristic Röntgen Radiations.

By R. Whiddington, B.A., St. John's College, Cambridge.

(Communicated by Sir J. J. Thomson, F.R.S. Received April 29,—Read May 25, 1911.)

We know from the researches of Barkla and Sadler and others that many of the phenomena in connection with the emission of secondary Röntgen rays can be explained quite simply by supposing that there are two distinct ways in which matter subjected to the action of primary rays may itself become a centre of radiation :—

(1) The primary rays may be scattered—an effect which is always very small.

(2) The primary rays may be transformed into a type of radiation characteristic of the transforming material and re-emitted as such.

This latter type of secondary radiation has been variously termed "characteristic," "homogeneous," "fluorescent." Each of these terms is expressive, but the first is perhaps the best, and will be used below.

The more important points in connection with the production and properties of this type of radiation are as follows :—

(1) A characteristic radiation is homogeneous or nearly so.

(2) It is only when the primary rays contain a constituent more penetrating than the characteristic to be excited that the stimulation can be effected (whence the term "fluorescent").

(3) The penetrating power of a characteristic radiation increases with the atomic weight of the emitting element.

(4) The characteristic radiation is invariably accompanied by emission of corpuscles from the surface of the radiator.

The experiments to be described have to do with (2) and (3), and define the quality of the softest primary radiation which can stimulate a characteristic, in terms of the velocity of the cathode rays within the exciting X-ray tube. The experiments consist broadly in directing a stream of cathode rays of known velocity and intensity on to an anticathode, the primary Röntgen rays so produced falling on a secondary radiator. So long as the cathode rays possess a velocity less than a certain critical value (v_c) no characteristic rays are emitted, but above this speed they become appreciable.

The values of v_c for the radiators Cr, Fe, Ni, Cu, Zn, and Se have been determined in this sort of way.* The value of v_c for Al has been already given.†

The Apparatus.

The first experiments were performed with very simple apparatus, the velocity of the cathode rays being deduced from the length of the equivalent spark-gap when the tube was running. It was soon found, however, that beyond the fact that many of the characteristic radiations came in at velocities corresponding to potentials of about 10,000 volts, no more information could be obtained.

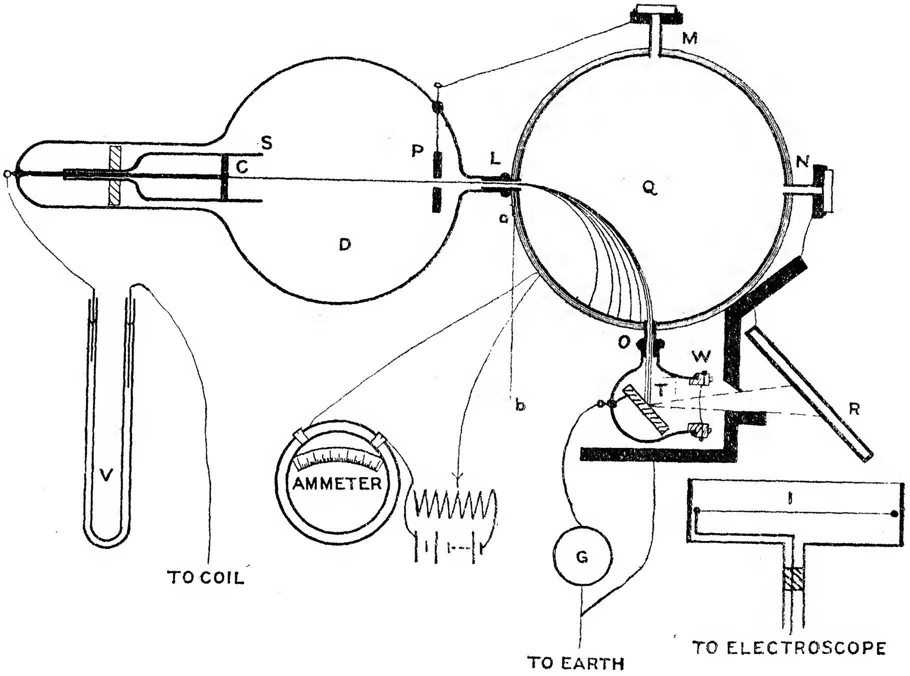

Fig. 1.

The form of apparatus finally adopted is indicated in fig. 1. It is perhaps not worth while to give in detail all the advantages of this particular form of apparatus; I may say, however, that an induction coil* is far more satisfactory to work with than the most recent form of influence machine (the Mercedes). The method consists in producing cathode rays in the ordinary way in a vacuum tube, spreading them out into a "magnetic spectrum," and sifting out the required velocity through a suitably placed aperture.

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* Preliminary results have been published in the 'Camb. Phil. Soc. Proc.,' 1911, vol. 16, p. 150.

† Whiddington, 'Roy. Soc. Proc.,' A vol. 85, p. 113.

D is a discharge tube fitted with the hardening device I have described to the Cambridge Philosophical Society.† By it the velocity of the cathode rays from C can be instantly changed to almost any desired value *without altering the gas pressure.* This bulb D furnishes a strong source of cathode rays, and is connected at L to a brass cylinder Q (shown in cross-section). L, M, N, and O are co-planar brass tubes 3 mm. in internal diameter, any pair of neighbouring tubes being at right angles. The cylinder Q is closed at each end and made vacuum tight; it is wound on the outside with four layers of No. 16 cotton-covered copper wire in solenoid fashion. The length of the cylinder is 35 cm., its diameter 10 cm.

When a current traverses the solenoid a very uniform and sharply bounded magnetic field is set up within the cylinder. A high "dispersion" can be effected in this way with very moderate exciting currents, the individual rays describing circles with centres on *ab*. It must be mentioned, however, that owing to the finite length of Q there is a small, but appreciable, magnetic force set up outside it when a current passes round the solenoid. This can easily be balanced out by means of a few turns of wire suitably placed, and in series with the solenoid.

The tubes M and N are for "sighting," and are closed at their ends with pieces of plate glass. The inside of Q is sprinkled with finely powdered Willemite so that the places struck by the cathode rays can be visually observed. The glass tube T is about 3 cm. in diameter, and contains a silver anticathode inclined as shown and mounted opposite a thin aluminium window W, through which the Röntgen rays escape. The inside of T is slightly silvered and metallically connected to the anticathode, which in its turn is joined to earth through the galvanometer G. The tube T thus functions as a Faraday cylinder, the reading of G giving the current carried by the cathode rays entering T, their velocity being given by the reading of the ammeter (since only those rays which are bent through a right angle can enter T).

R is a secondary radiator placed opposite the window W, and also opposite the ionisation chamber I, connected in the usual way to a Wilson tilted electroscope.

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* A Cox mechanical interrupter was used in preference to a mercury break.

† *Loc. cit.*

Now in these experiments the energy in the secondary rays measured in I is only a very small fraction of the energy in the primary rays striking R; the energy in these primary rays is again only a small fraction of the energy in the cathode rays striking the anticathode. It is therefore of great importance to make use of the largest possible fraction of the cathode rays emitted by C. The velocity-number distribution of the rays is given in fig. 2A, which is typical of the many curves at all sorts of velocities which have been obtained. It is very convenient that there should be such a considerable concentration of the rays into the highest velocity end of the spectrum; since, by setting this maximum on the centre of O, one not only makes use of the largest possible number of cathode rays, but, at the same time, one fulfils the condition necessary for their greatest possible homogeneity, a point which will now be gone into in more detail.

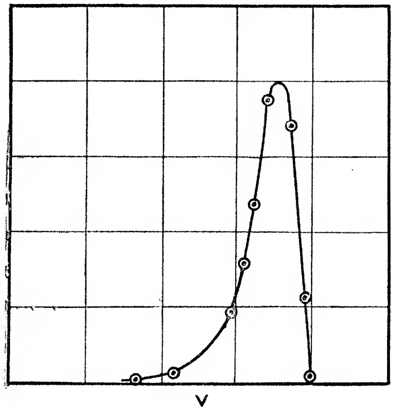

Fig. 2A.

Fig. 2B represents an imaginary spectrum distribution in a beam of rays 3 mm. wide (on emerging from L) as analysed by a very fine aperture at O. There is an apparent range of velocities in this flat-topped maximum corresponding to its width *pq*; but the thick-line curve may be regarded as made up of a large number of smaller similar curves contributed by the different elements of the aperture L. The actual velocity of the rays included in the

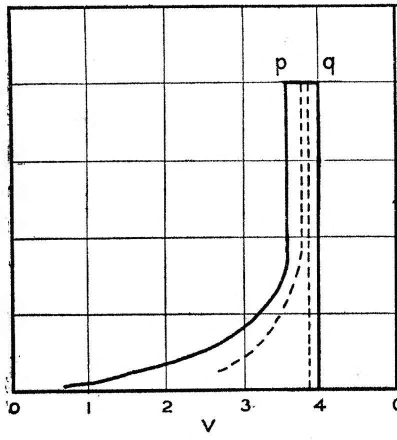

Fig. 2B.

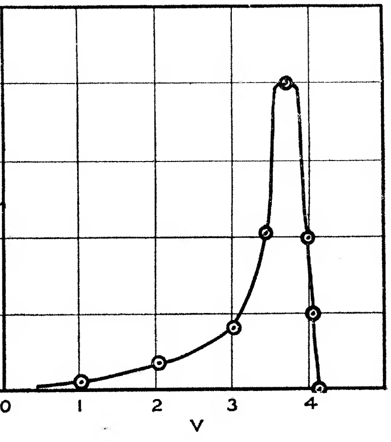

Fig. 2C.

apparent range *pq* will be that corresponding to the central element (represented by the dotted curve).

Now the distribution in fig. 2B, if analysed by an aperture 3 mm. wide at O, would give the apparent distribution of fig. 2C—a curve very similar to that experimentally obtained (fig. 2A). It is therefore allowable to use the imaginary curve of fig. 2B (which gives a close approximation to the true distribution) to estimate the constitution of the rays entering T.

It comes out that when the maximum of the curve falls on the centre of O, 70 per cent. of the rays entering T have a velocity v (corresponding to the rays entering at the centre of O and coming from the centre of L), while the remaining 30 per cent. have velocities ranging between v and $0{\cdot}955v$. If there had been an impartial distribution in the spectrum and O were placed in the middle, then the rays entering T would have possessed velocities ranging *continuously* between about $1{\cdot}045v$ and $0{\cdot}955v$.

A few remarks are necessary as to the calculation of the velocity of the rays from the strength of the current in the magnetic solenoid.

The formula connecting the radius r of the circular path described by a particle of mass m and carrying a charge e in a uniform magnetic field of strength H is

$$v = \mathrm{H}\,.\,r\,.\,e/m, \quad \text{where} \quad e/m = 1{\cdot}77 \times 10^7 \text{ E.M.U.} \tag{1}$$

In this particular case r is invariable and very nearly equal to the mean radius of the solenoid producing the magnetic field. H on the other hand is variable, its value depending on the current (c) in the solenoid. The relation $\mathrm{H} = gc$ gives the connection between H and c, the constant g depending on the shape and winding of the solenoid. It is not altogether satisfactory to rely on the value of g found from a formula, since in addition to the solenoid having a finite (and not accurately known) length, it has a gap in the middle through which the tubes L, M, N, and O pass. The value of g was therefore determined experimentally by measuring H with a search coil and galvanometer. As a matter of fact g found in this way differed only slightly from the value calculated from the dimensions of the solenoid.

g was found in yet another way, or what amounts to the same thing, a direct connection between c and v was obtained. The method was to produce homogeneous cathode rays with an influence machine at a potential V, noting at the same time the current c required to deflect them through a right angle to O. The velocity of the rays is obtained from the relation

$$\tfrac{1}{2}mv^2 = e\,.\,\mathrm{V}.$$

v found in this way differed by not more than 1 per cent. from that got by calculating H from the formula $\mathrm{H} = gc$, and substituting in (1).

This must mean, of course, that in this apparatus the cathode rays really fall through the whole potential V.

It is convenient to conclude this description of the apparatus with a brief account of the instruments used.

The Ammeter.—A Weston instrument reading up to 5 ampères in steps of 0·05. It could be read by estimation to 0·005 ampère.

The Galvanometer.—A dead beat instrument of the d'Arsonval type giving one division deflection for 10^{-7} ampère.

The Electroscope.—A Wilson tilted instrument giving 45 eyepiece divisions per volt. The capacity of the whole system was about 8 cm. It was connected to a variable multiple plate air condenser, by means of which the capacity could be increased to 100 cm., or to any of four intermediate values. By this means the sensibility could be suited to the charge to be measured without the trouble of altering the tilt of the instrument.

The Experiments.

The first experiment was to see how the actual primary Röntgen ray energy (E_p) escaping through W depended on the velocity v of the cathode rays striking the anticathode. To do this the radiator R was replaced by the ionisation chamber I. After correcting the observed values of the ionisation currents for the variations of the absorption coefficients of the Röntgen rays with v, it comes out that E_p (per unit cathode ray current) is nearly proportional to v^4, a result deduced theoretically by Sir J. J. Thomson some years ago).* Further experiments have been carried out in this connection which cannot fitly be given here.

To turn now to the emission of secondary rays by radiators placed in the path of this primary radiation. Some of the results are given graphically in fig. 3.† v^4 is measured along the x axis, while E_s, the secondary energy observed in I, is measured along the y axis.

For the sake of clearness, only the curves for the radiators Cr, Cu, and Se are there shown. Exactly similar curves obtain for Fe, Ni, and Zn.

The following table (p. 330), copied direct from the laboratory note-book, indicates the method of taking observations.

The product itk' gives a number inversely proportional to E_s. The mean of some five or six sets of results such as the above go to the making of a single curve.

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* "The Electrical Origin of Radiation," 'Phil. Mag.,' August, 1907.

† These curves are not all drawn to the same scale.

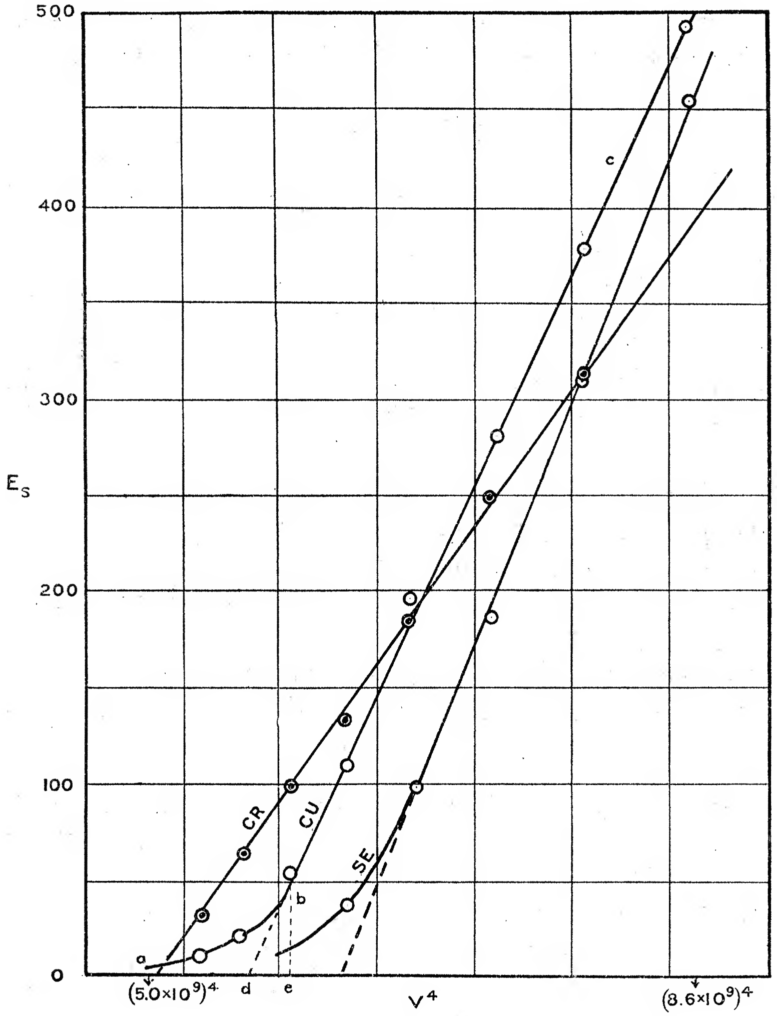

FIG. 3.

The curve for Cu is typical. It is seen to consist (fig. 3) of two parts *ab* and *bc*, having very different slopes and a fairly sudden transition point at *b*. The part *ab* represents quite small values of E_s (see above table), and there is no reason to suppose that it is a straight line, since it must be due to scattered radiation, whose absorption coefficient is diminishing as v increases. The part *bc*, on the other hand, is obviously a straight line, and is due almost entirely to the very intense characteristic radiation emitted by R after the point *b* has been passed. (This was proved by measuring the absorption of the rays in aluminium, and comparing with the values given by Barkla and Sadler.) It may be pointed out in passing that theoretically one might have expected *bc* to have been somewhat concave to the *x*-axis, on the assumption, that is, that E_s is proportional to E_p.

Cu radiator.

c.	*i*.	*d*.	*t*.	*k*.	*itk′*.	E_s.
2·80	20·0	10	128·0	0	2560	21·5
3·00	20·0	10	57·5	0	1150	47·8
3·20	22·0	10	25·0	0	550	100
3·40	30·0	10	27·6	3	248	222
3·60	16·0	10	28·7	3	138	398
3·80	14·0	10	23·4	3	98·0	562
4·00	9·0	10	27·0	3	72·8	758
4·20	7·0	10	26·6	3	55·8	990

In this table—

c = the current in the solenoid.

i = the cathode ray current (the reading of G).

d = the number of microscope eyepiece divisions travelled by the gold leaf in the mean time t.

k = the number denoting the capacity used on the leaf.*

E_s = the secondary energy emitted by R per unit cathode ray current entering T (fig. 1).

It is now necessary to consider the best way of obtaining the position of the point *b*. If *cb* be produced, it will cut the *x* axis in *d*. In the absence of the part *ab* of the curve, this point *d* would give accurately the critical value v_c^4. As it is, however, this gives too small a value. The true value must lie between *od* and *oe*. The only method available seems to be to take the mean $\frac{1}{2}(od+oe)$ as giving the best possible value of v_c^4. If, in applying this correction, an error so large as 4 or 5 per cent. be introduced, it will only mean an error of about 1 per cent. in v_c.

The following table gives the results :—

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* To the capacity designated by k corresponds a factor k' such that if t is the time taken by the leaf to traverse d divisions when connected to the capacity k, tk' is the time it would have taken to perform the same journey had it been connected to the standard capacity 0. Thus, in this table $k' = 0·300$ for capacity 3 which means that a time of (say) 10 seconds with this capacity would reduce to only 3 seconds for the standard capacity 0.

Radiator.	V_c.	$v_c \times 10^{-9}$.	Atomic weight.	*m*.	λ/ρ.*
Al	1200	2·06	27·0	—	580
Cr	7320	5·09	52·5	10·0	136
Fe	9600	5·83	56·0	30·0	88·5
Ni	10750	6·17	58·6	46·5	59·1
Cu	11080	6·26	63·2	59·1	47·7
Zn	11280	6·32	65·1	72·7	39·4
Se...............	15400	7·38	78·9	91·0	18·9

* These values of λ/ρ, with the exception of that for Al, are taken from a paper by Barkla and Sadler, 'Phil. Mag.,' 1908.

In this table—

v_c = the critical cathode ray speed.

V_c = the corresponding potential in volts, *i.e.*, that potential above which an ordinary X-ray tube supplied with a steady voltage would have to run, in order to excite the radiation characteristic of the element placed in the same line in the table.

m = the slope in arbitrary units of the straight line representing the connection between E_s and v^4.

λ/ρ = the absorption coefficient of the radiation concerned.

[Particular reference must be made to Al, which figures in the above table. In the paper referred to above, evidence was brought forward indicating that Al does not obey the "fluorescence law" to which the elements studied by Barkla and Sadler certainly conform. This would explain the rather low value of v_c.]

The above table shows that, at any rate, an approximate linear relation exists connecting v_c and the atomic weight.*

It was not possible to work with cathode rays moving faster than about 10^{10} cm./sec., on account of the difficulty of making the tube run steadily; up to this velocity, however, the radiation characteristic of silver could not definitely be detected.

The Cr curve in fig. 3 was obtained, using a radiator made of the pure element. I have tried a radiator consisting of a plane plate of sodium bichromate and have found that both v_c and m are the same as for the element within experimental error.

Experiments on the emission of corpuscles by secondary radiators are now in progress. It seems advisable to reserve discussion of the above results until these experiments be concluded.

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* If hydrogen emit a characteristic radiation conforming to this law, the values of v_c and V_c would be 10^8 cm./sec. and 2·82 volts respectively.

Summary of Experimental Results.

(1) The energy emitted in the form of Röntgen radiation by a cathode particle when suddenly stopped is proportional to the fourth power of its velocity.

(2) The primary rays from a Röntgen ray tube can only excite the radiation characteristic of a radiator of atomic weight w when the velocity of the parent cathode rays exceeds $w \times 10^8$ cm./sec.

This law holds fairly closely for the radiators Al, Cr, Fe, Ni, Cu, Zn, and Se.

It gives me pleasure to thank Prof. Sir J. J. Thomson for the interest he has taken in these experiments.

Experiments on the Compression of Liquids at High Pressures.

By the Hon. C. A. Parsons, C.B., F.R.S., and S. S. Cook, B.A. Cantab.

(Received May 10,—Read May 25, 1911.)

1. *Introduction.*

During the experiments on the behaviour of carbon under high pressures and temperatures, of which an account was given in the paper read before this Society by the Hon. C. A. Parsons on June 27, 1907, very considerable volumetric compressions were observed, and the apparatus then employed appeared to be equally suitable for the direct measurement of the compressibility of liquids at higher pressures than had previously been attempted.

The measurement of the compressibility of liquids has received the attention of a great many investigators; the most comprehensive researches in this subject appear to be those of Amagat, who determined the coefficients of compressibility of water and ether for pressures up to 3000 atmospheres and for a variety of temperatures. Amagat's experiments are given in various numbers of 'Comptes Rendus.'* In the experiments about to be described, the pressures were carried up to about 40 tons per square inch, or over 6000 atmospheres.

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* 'Comptes Rendus,' vol. 103, p. 429; vol. 105, p. 1120; vol. 107, p. 522; vol. 108, p. 228; vol. 111, p. 871.